FLOW STRUCTURE AND MASS TRANSFER INVESTIGATION OF THE TURBULIZED BOUNDARY LAYER WITH ETHANOL EVAPORATION AND DIFFUSION COMBUSTION

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Introduction

In the real technical devices, the level of turbulence is usually high. For instance, we have Tu_o=2-20% at entrance to a gas turbine. At a considerable part of turbine-blade surface (50-80%) exposed to combustion products, the boundary layer is in the state of laminar-turbulent transition, which occurs without the formation of instability waves and with closed separation. This kind of flow is the subject of research in the present paper and the problem includes all the diversity of factors (flow separation, laminar-turbulent transition at an elevated turbulence, combustion). They are interrelated, so their joint impact on gas-dynamic characteristics of flow and transfer processes is of greate importance.

The effect of the separation region on the flow structure and also on heat and mass transfer under conditions close to isothermal one was studied in [1-3]. At the reattachment point located at a distance of 10-18 height *h* from the obstacle, friction stress changes its direction; turbulence and intensity of transfer processes increase, inrush of the liquid to the wall and its outbursts into the main flow are observed. The rate of heat and mass transfer behind an obstacle can significantly increase.

With turbulization of the flow core, the size of separation zone decreases, and the cross-flow scales increase though to different extents: the thermal boundary layer becomes thicker than dynamic one. The momentum thickness δ^{**}, which determines friction in the case without injection and pressure gradient, remained almost unchanged at a distance of 0.65 m in the experiments of [4].

During combustion, flow reattachment is observed at a distance of (6-9)*h* [5]. In the region of relaxation heat and mass transfer exhibits properties of laminar flow [6]. Obviously, the structure of the reacting boundary layer is a result of interaction of turbulence and combustion. In experiments with plume, possible deceleration of mixing due to laminarization and, vice versa, additional turbulization in the boundary layer upon interaction of gases of different densities were noted.

Uncertainty of evaluation of each factor (separation, laminar-turbulent transition, combustion, and turbulization) hinders mathematical simulation of the joint effect on gas dynamic and thermal characteristics of the boundary layer. The characteristics may be most reliably determined experimentally. The work objective is the experimental study of the boundary layer structure, comparison of the fields of temperature, velocity and its pulsation with data on heat and mass transfer.

Experimental Setup and Measurement Procedure

Experiments were performed on a wind tunnel, with a wire mesh 1×1 mm at the confusor inlet (for Tu_o =1%) or a grid with 25 screwed holes M27×1.5. When some of the holes were plugged, the turbulence level at the inlet to the working section increased up to Tu_o = 8, 18%. The channel cross-section is 100 × 100 mm^2, there is no wall on the top and the lateral walls are

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transparent and made of a set of quartz sheets. The working section models the combustion chamber of a ramjet engine; it has an all-width rib with variable height h = 1,5-15 mm at the section entrance. There is a bleed slot for a boundary layer with the width of 8 mm. In experiments with laser anemometer, the bottom surface was made renewable: there were five square 80×80 mm^2 trays filled up with glass beads with the diameter of 0.7±0.15 mm. The packing of beads (the depth was 8 mm) can be renovated after contamination. For mass transfer experiments, we used porous metal sheets made from stainless steel. It was shown that values of momentum thickness for these kinds of surfaces measured under isothermal conditions are equal each other.

The temperature of the stream-face surface T_w was measured by chromel-alumel thermocouples. The working liquid was 96% ethanol. The ethanol mass concentration on the wall C_w was determined from T_w using a saturation curve (it was 0.03 without combustion and 0.8 with combustion). The feeding system provided a constant level of the fluid fuel in a porous material, which has to be wetted during the entire experiment. The non-dimensional ethanol flux from every element of the wall is $J = J_w/\rho_o U_o$; it has self-adjusted according to the conditions of convective mass transfer and it was calculated form a change of its level in the supplying vessels. Here J_w [kg/m^{2}s] is the evaporation rate; ρ_o and U_o are the density and velocity of air in the main stream. From this data, the diffusion number of Stanton $St_d = J/C_w$, with accuracy of 15%. The velocity U_o of a turbulent flow (with the temperature $T_o = 290$K) was found from the pressure drop on a flow-meter washer. The temperature in the boundary layer was measured by platinum/platinum-rhodium thermocouple with the diameter of 50 μm. The data obtained was corrected to compensate radiate losses of the probe.

Without combustion the measurements are performed with help of a DISA hot-wire anemometer (single-wire probe, wire diameter 8 μm, 55M01 bridge and 55D10 linearizer). A laser Doppler anemometer measured the longitudinal velocity component u in the combustible boundary layer. The scattering centres were 1-micron particles of quartz; they were fed into the airflow directly in the confusor after the grid or mesh. The optical system of the LADO-2 anemometer and the source of radiation (an LG-79-1 He-Ne laser of power 15 mW) were located at the platform of traversing gear above the test section). Beams of approximate power of 3 mW were focused in the region of intersection of volume $0.1\times0.1\times0.5$ mm and entered the test section through a slot approximately 10 mm wide between the separated quartz plates of sidewall. Radiation scattered on particles was removed from the channel through a similar slot on the opposite wall and was registered by photomultiplier. The signal was identified by tracking filter [7].

In preliminary experiments without combustion in a flow powdered by 1-micron glycerine aerosol and quartz powder, it was found that in both cases the spectra of longitudinal velocity fluctuations coincide with each other and with hot-wire data, if the response time of the equipment is minimum and number concentration of particles flying over control volume is approximately 10^3 sec^{-1}. In the case of combustion, the signal-to-noise ratio decreases, and the threshold values of the signal are increased to ensure stable operation of equipment, i.e., the number concentration of particles and measured level of turbulence are artificially reduced to certain level. Thereby the RMS value of (u') was corrected until the measured level of turbulence at the channel entrance coincided with the hot-wire data. It was assumed that only the intensity of velocity fluctuations changes at different points. In our estimates, this leads to an increase in the error of Tu determination up to 20% but does not effect the final results, which depend on the unchanged tuning of the tracking filter: constant response time, degree of signal filtration, and number concentration of particles.

Experimental Results and Discussion

In the case of no combustion, the minimal deviation from the calculated curve (St = 0.029 $Re_x^{-0.2}$) for turbulent boundary layer was observed at Tu_o =1% and h=3mm, Fig. 1. Here are the set of curves $St = \Psi_p 0.332\ Re_x^{-0.5}$, with Ψ_p= 1, 2, 3…[6]. The Stanton number data reach extremum at the reattachment region, then we can see the extended sites where Stanton and Reynolds numbers are connected as St ~ $Re^{-0.5}$. This data concern to the separated flows of different types. But usually the relations such as St ~ $Re^{-1/3}$ [3] (so-called "two third law", since Nu~$Re^{2/3}$) are used to summarise experimental results.

If combustion, the longitudinal size of the recirculation region are in close agreement with data [5]. Figure 2 shows the mass fluxes downstream of the reattachment zone. With a higher rib *h*=6-15mm, a jump-like growth of the burnout velocity takes place. The results of experiments are appreciably stratified. At high turbulence (Tu_o=18%, *h*=15 mm) one can see the increasing of mass transfer, and the maximum of $J_w/\rho_o U_o$ appears again. The positions of these two particular qualities can be easily identified on the packing surface by more intensive places of powder fallout (it was used to make a dust-laden mainstream). It seems to be similar to situation when the several reattachment regions arise.

The thickness of a dynamic boundary layer varies slowly if Tu_o < 18%, see Fig. 3. As the mainstream turbulence increases, the gradient of average velocity $\Delta U/\Delta y$ might not only increase, but to decrease as well. The shape of profiles varies in a wide range, approaching to the calculation curves both for turbulent boundary layer $\omega = u/U_o = (y/\delta)^{1/7}$ (curve 1), and laminar one (curve 2). With a growth in Tu_o, the turbulence level in the boundary layer increases drastically: if for Tu_o=2.7% it was close to the no-combustion case (curve 3), then at Tu_o=8% it

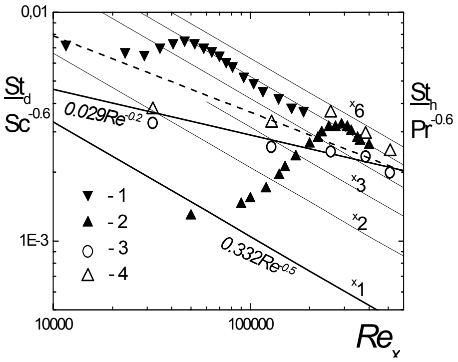


Fig. 1. Heat and mass transfer in the separated and reattached boundary layer without combustion: 1 – streamlining of the blunt plate [1]; 2 – backstep [2] *h* = 30 mm, Tu_o = 1.5%. The hollow points – present work data on the mass transfer after rib: 3 – *h* =3 mm, Tu_o= 1%, 4 – *h* = 6 mm, Tu_o= 18%. Dushed line – "two thirds law " [3].

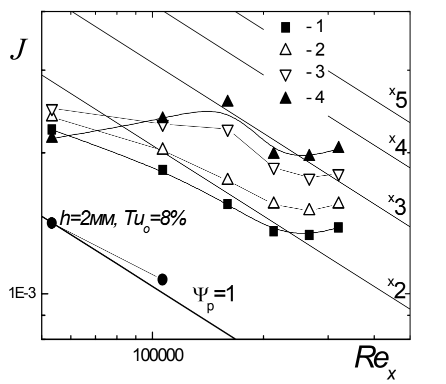


Fig. 2. Change in mass transfer intensity for evaporation and combustion of ethanol at U_o = 10 m/s and Tu_o= 18%: 1 – *h*= 6 mm; 2 – *h* = 9 mm; 3 – *h* = 9 mm; 4 – *h* = 12 mm; 2 – *h* = 15 mm;
Curves corresponds to $J = \psi_p 0.41 Re^{-0.5} C_w$;
ψ_p = 1, 2, 3…

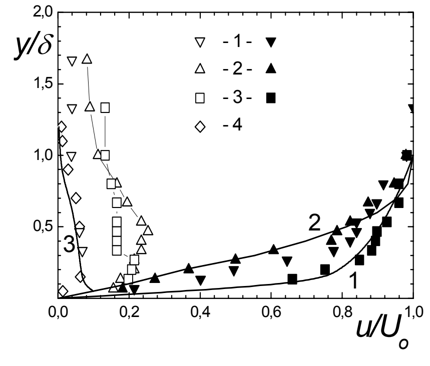


Fig. 3. Profiles of the longitudinal average velocity (bold symbols) and RMS velocity pulsations in a turbulized boundary layer with evaporation and combustion of ethanol (h= 3 mm, U_o = 10 m/s, x = 140 mm) for different values of Tu_o : 1 – 2.7%, 2 – 8%, 3 – 18%, 4 – data from [8] for Tu_o = 0.7% and x = 120 mm, 1 – turbulent boundary layer without combustion. Even at Tu_o = 18% we see a resemblance with Blasius' profile (curve 2).

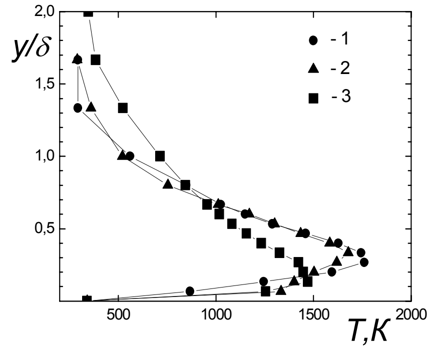


Fig. 4. Growth of the thermal boundary layer thickness due to combustion with turbulization of the main stream. The average temperature profiles corresponds to conditions described in captions to Fig.3 (h = 3 mm, U_o = 10 m/s, x = 140 mm) for different values of Tu_o: 1 – 2.7%, 2 - 8%, 3 – 18%.

reaches a maximum. This maximum, away from the wall, has Tu_{max} >25%. The data of [8] corresponds to injection of the $H_2 + N_2$ mixture and its combustion in air (U_o = 10 m/s and Tu_o = 0.7%) under conditions there the dynamic boundary layer is developed upstream and is thicker than the thermal boundary layer (x_o = –1 m and δ = 40 mm).

The further increase Tu_o results in changes on the average movement and, at last, can cause qualitative reorganisation of current, and so not for all values of h and Tu_o was it possible to perform experimental investigations of the combustible boundary layer. Preliminary tests with combustion in a turbulized flow showed that region where the flame is stabilised by rib is restricted, Fig. 5. For Tu_o =1% and h < 3 mm, the flameout was observed already at flow velocities of 3-5 m/s, whereas for h =3 mm the flame is stable in a wide range of velocities, which becomes narrower with increasing of turbulence level and wider with increasing rib height. The flameout velocity U_b reaches the highest value at certain value of h and Tu_o.

Combustion provides good visualisation of the flow, due to which it was established that the flameout occurs directly behind circulation zone, presumably at the flow reattachment point. The flameout can be reversible. In tests with Tu_o > 8%, h > 6mm, for instance, with $U > U_b$ combustion is

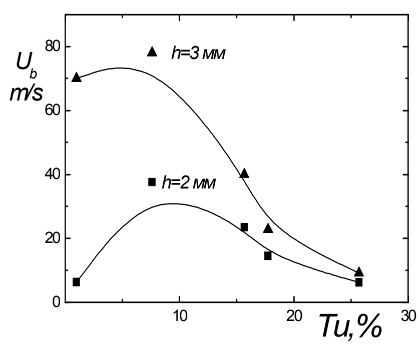
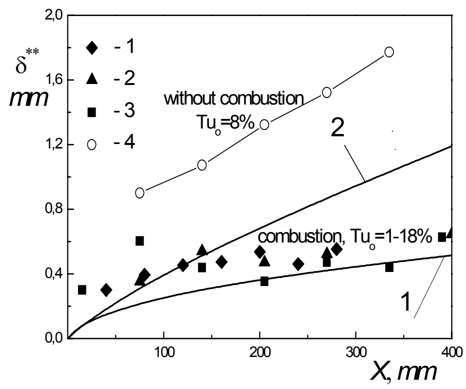


Fig. 5. The effect of free stream turbulence and obstacle height on flameout velocity U_b in the case of ethanol evaporation and combustion into boundary layer.

Fig. 6. The momentum thickness along of turbulent boundary layer at U_o = 10 m/s and h = 3mm. Bold symbols are the experiment with ethanol evaporation and combustion at different Tu_o : 1 – 1%, 2 – 8%, 3 – 18%; light symbols (4) – combustion (h = 3 mm, Tu_o = 8%). Data approaches the calculation curve for laminar flow.



retained only upstream of the reattachment point. If the flow velocity is now decreased ($U < U_b$), the flame appears again throughout the entire channel length [9].

The deformation of temperature profiles in turbulized boundary layer is shown in Fig. 4: with growth of Tu_o its maximums decrease, and their positions draw back to the wall. The thickness of the thermal boundary layer (the ordinate on the temperature profile where it is T = 300K) can be twice higher than the dynamic thickness δ. The reason seems to be the difference in density of the interacting flows. Portions of the cold gas from the main flow penetrate deeper into the near-wall region and, interacting with high-temperature combustion products, cause outbursts of large volumes of the heated gas into the outer part of the boundary layer.

The data obtained allow us to determine the integral scales of the turbulized combustible boundary layer. The displacement $\delta^* = \int(1-\rho\omega)dy$ increase during turbulization by the factor of 1.5÷2; it even can be 20 times higher than the thickness of a standard boundary layer (isothermal streamlining of a smooth impermeable wall). The change of the momentum thickness $\delta^{**} = \int\rho\omega(1 - \omega)dy$ over the channel length is shown in Fig. 6. It must characterise friction: with/without combustion we have $d\delta^{**}/dx = C_f/2$. Curve 2 corresponds to a standard turbulent flow. For the combustion mode, for x >200 mm and for all Tu_o the data on $\delta^{**}(x)$ tend to approach. This data is close to calculation for friction in a laminar isothermal flow without blowing $\delta^{**} = 0.664(\nu x/U_o)^{0.5}$ (curve 1). For a high initial turbulence Tu_o=18%, the momentum thickness on the distance x =75÷205 mm decreases. Similar phenomenon was observed for experiments without combustion [4].

Conclusions

The present study shows that turbulization has a strong effect on the boundary layer structure with combustion. In experiments, turbulization was exited both in the main flow and in an immediate vicinity of the wall behind a variable-height obstacle. If Tu_o ~3%, the turbulence intensity in flame front is approximately equal to one in the boundary layer without combustion. If Tu_o ~8%, the velocity pulsations increases drastically. Further increase Tu_o can cause flow reorganization and flameout. The grate stratification of measured characteristics of heat and mass transfer takes place. It was found that the friction in combustible boundary layer close to friction in laminar isothermal flow even the level of main stream turbulence is very high (Tu_o = 18%). The data obtained may be useful for development of a physical model of a turbulent wall flow and for analysis of combustion process in power installations.

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